

KALEIDOSCOPICAL CONFIGURATIONS IN G -SPACES

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ABSTRACT. Let G be a group and X be a G -space with the action $G \times X \rightarrow X$, $(g, x) \mapsto gx$. A subset F of X is called a kaleidoscopic configuration if there exists a coloring $\chi : X \rightarrow C$ such that the restriction of χ on each subset gF , $g \in G$, is a bijection. We present a construction (called the splitting construction) of kaleidoscopic configurations in an arbitrary G -space, reduce the problem of characterization of kaleidoscopic configurations in a finite Abelian group G to a factorization of G into two subsets, and describe all kaleidoscopic configurations in isometrically homogeneous ultrametric spaces with finite distance scale. Also we construct 2^c many (unsplittable) kaleidoscopic configurations of cardinality c in the Euclidean space \mathbb{R}^n .

INTRODUCTION

Let X be a set and \mathfrak{F} be a family of subsets of X (the pair (X, \mathfrak{F}) is called a *hypergraph*). Following [4], we say that a coloring $\chi : X \rightarrow \kappa$ of X (i.e. a surjective mapping of X onto a cardinal κ) is

- \mathfrak{F} -*surjective* if the restriction $\chi|_F$ is surjective for all $F \in \mathfrak{F}$;
- \mathfrak{F} -*injective* if $\chi|_F$ is injective for all $F \in \mathfrak{F}$;
- \mathfrak{F} -*bijective* or \mathfrak{F} -*kaleidoscopic* if $\chi|_F$ is bijective for all $F \in \mathfrak{F}$.

A hypergraph (X, \mathfrak{F}) is called *kaleidoscopic* if there exists an \mathfrak{F} -kaleidoscopic coloring $\chi : X \rightarrow \kappa$. The adjective "kaleidoscopic" appeared in definition [5] of s -regular graph $\Gamma(V, E)$ (each vertex $v \in V$ has degree s) admitting a vertex $(s+1)$ -colloring such that each unit ball $B(v, 1) = \{u \in V : d(u, v) = 1\}$ has the vertices of all colors (d is a path metric on V). These graphs can be considered as a graph version of Hamming codes [6].

We shall consider hypergraphs related to G -space. Let G be a group. A G -space is a set X endowed with an action $G \times X \rightarrow X$, $(g, x) \mapsto gx$. All G -spaces are suppose to be transitive (for any $x, y \in X$ there exists $g \in G$ such that $gx = y$). For a subset $A \subseteq X$, we put $G[A] = \{gA : g \in G\}$.

A subset $A \subseteq X$ is called a *kaleidoscopic configuration* if the hypergraph $(X, G[A])$ is kaleidoscopic (in words, if there exists a coloring $\chi : X \rightarrow |A|$ such that $\chi|_{gA}$ is bijective for every $g \in G$).

In Section 1 we show that kaleidoscopic configurations are tightly connected with classical combinatorial theme *Transversality* and, in the case $X = G$ and (left) regular action of G on G , with factorization problem, well known in *Factorization Theory of groups*, see [11], [12].

In Section 2 we introduce and describe the kaleidoscopic configurations (called splittable) which arise from the chains of G -invariant equivalences (imprimitivities) on X . If a G -space X is primitive (the only G -invariant equivalences on X are $X \times X$ and Δ_X) then the only splittable configurations in X are X and the singletons.

In Section 3 we prove that every kaleidoscopic configuration in isometrically homogeneous metric space with finite distance scale is splittable. For $n \geq 2$, we construct a plenty of kaleidoscopic configurations of cardinality c in \mathbb{R}^n . These configurations are non-splittable because \mathbb{R}^n is isometrically primitive. We don't know whether there exists a finite non-singleton or countable kaleidoscopic configurations in \mathbb{R}^n , $n \geq 2$.

In Section 4 we study the problem of splittability of kaleidoscopic configurations in finite Abelian groups and reformulate this problem in terms of the semi-Hajós property, see [11], [12].

1. TRANSVERSALITY AND FACTORIZATION

Let (X, \mathfrak{F}) be a hypergraph. A subset $T \subseteq X$ is called an \mathfrak{F} -transversal if $|F \cap T| = 1$ for each $F \in \mathfrak{F}$.

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Proposition 1.1. *A hypergraph (X, \mathfrak{F}) is kaleidoscopic if and only if X can be partitioned into \mathfrak{F} -transversals.*

Proof. For a kaleidoscopic hypergraph (X, \mathfrak{F}) , let $\chi : X \rightarrow \kappa$ be a kaleidoscopic coloring. Then $\bigsqcup_{\alpha < \kappa} \chi^{-1}(\alpha)$ is a partition of X into \mathfrak{F} -transversal.

On the other hand, if $\bigsqcup_{\alpha < \kappa} T_\alpha$ is a partition of X into \mathfrak{F} -transversal then the coloring $\chi : X \rightarrow \kappa$ defined as $\chi(x) = \alpha \Leftrightarrow x \in T_\alpha$ is kaleidoscopic. \square

Let X be a G -space A be a kaleidoscopic configuration in X . If T is $G[A]$ -transversal then A is $G[T]$ -transversal and gT is $G[A]$ transversal for each $g \in G$.

We say that a kaleidoscopic configuration A in X is *homogeneous* if there exist a $G[A]$ -transversal T and a subset $H \subseteq X$ such that $X = \bigsqcup_{h \in H} hT$.

A subset A of a group G is defined to be *complemented* in G if there exists a subset $B \subseteq G$ such that the multiplication mapping $\mu : A \times B \rightarrow G$, $(a, b) \mapsto ab$, is bijective. Following [12], we call the set B a *complement factor* to A , and say that $G = AB$ is a factorization of G . In this case, we have

$$G = \bigsqcup_{a \in A} aB = \bigsqcup_{b \in B} Ab.$$

A subset $A \subseteq G$ is called *doubly complemented* if there are factorization $G = AB = BC$ for some subsets B, C of G .

Proposition 1.2. *For two subsets A, B of a group G the following conditions are equivalent:*

- (1) B is $G[A]$ -transversal;
- (2) $G = AB^{-1}$ is a factorization of G .

Proof. (1) \Rightarrow (2) For each $g \in G$, $g^{-1}A \cap B \neq \emptyset$, so $g \in AB^{-1}$. If $g = a_1b_1^{-1} = a_2b_2^{-1}$ for some $a_1, a_2 \in A$, $b_1, b_2 \in B$, then $g^{-1}a_1 = b_1$ and $g^{-1}a_2 = b_2$ and by (1), $b_1 = b_2$ and $a_1 = a_2$, witnessing that $G = AB^{-1}$ is a factorization of G .

(2) \Rightarrow (1) Fix any $g \in G$. The inclusion $g^{-1} \in AB^{-1}$ implies $gA \cap B \neq \emptyset$. If $ga_1 = b_1$ and $ga_2 = b_2$ for some $a_1, a_2 \in A$, $b_1, b_2 \in B$, then $g^{-1} = a_1b_1^{-1} = a_2b_2^{-1}$ and by (2), $b_1 = b_2$, witnessing that $|gA \cap B| = 1$. \square

Corollary 1.3. *Each kaleidoscopic configuration in group G is complemented.*

Proof. Given a kaleidoscopic configuration $A \subset G$, fix a A -kaleidoscopic coloring $\chi : G \rightarrow C$. We choose a color $c \in C$, consider the monochrome class $B = \chi^{-1}(c) \subset G$ and observe that for every $g \in G$ $|gA \cap B| = 1$ by the definition of A -kaleidoscopic coloring. By Proposition 1.2, $G = AB^{-1}$ is a factorization, so A is complemented in G . \square

Proposition 1.4. *A subset A of a group G is doubly complemented if and only if A is a homogeneous kaleidoscopic configuration.*

Proof. Let $G = AB = BC$ be a factorization of G . By proposition 1.2, B^{-1} is a $G[A]$ -transversal. Since $G = \bigsqcup_{c \in C} c^{-1}B$, we conclude that A is a homogeneous kaleidoscopic configuration.

Let A be a homogeneous kaleidoscopic configuration. We choose a $G[A]$ -transversal T and a subset $H \subseteq G$ such that $G = \bigsqcup_{h \in H} hT$. By proposition 1.2, $G = AT^{-1}$. Since $G = \bigsqcup_{h \in H} hT$, $G = T^{-1}H^{-1}$ is a factorization. Hence, A is doubly complemented. \square

Corollary 1.5. *For a subset A of an Abelian group G , the following statements are equivalent:*

- (1) A is complemented;
- (2) A is a kaleidoscopic configuration;
- (3) A is a homogeneous kaleidoscopic configuration.

Question 1.6. *Is each complemented subset of a (finite) group kaleidoscopic?*

Proposition 1.7. *Let X be a G -space, $x \in X$, $G_x = \{g \in G : gx = x\}$, $\gamma_x : G \rightarrow X$, $\gamma_x(g) = gx$, $s : X \rightarrow G$ be a section of γ_x . Let A be a subset of X , T be $G[A]$ -transversal. Then*

- (1) $s(T)$ is a $G[\gamma_x^{-1}(A)]$ -transversal;
- (2) $|G| = |G_x||A||T|$.

Proof. The statement (1) is evident. The statement (2) follows from (1) and proposition 1.2. \square

Corollary 1.8. *Let A be a kaleidoscopic configuration in a finite G -space X with a kaleidoscopic coloring $\chi : G \rightarrow k$. Then $\chi^{-1}(0) = \dots = \chi^{-1}(k-1)$ and $|X| = |A||\chi^{-1}(0)|$.*

Proof. We may suppose that G is a subgroup of the group of all permutations of X so G is finite. Since $|G| = |X||G_x|$, we can apply proposition 1.7(2). \square

Proposition 1.9. *Let κ be an infinite cardinal, (X, \mathfrak{F}) be a hypergraph such that $|\mathfrak{F}| = \kappa$ and $|F| = \kappa$ for each $F \in \mathfrak{F}$. If $|F \cap F'| < \text{cf} \kappa$ for all distinct $F, F' \in \mathfrak{F}$ then there are a disjoint family \mathfrak{T} of \mathfrak{F} -transversals such that $|\mathfrak{T}| = \kappa$, $|T| = \kappa$ for each $T \in \mathfrak{T}$*

Proof. We enumerate $\mathfrak{F} = \{F_\alpha : \alpha < \kappa\}$ and choose inductively the subsets $\{V_\alpha \subset F_\alpha : \alpha < \kappa\}$ such that the family $\{F_\alpha \setminus V_\alpha : \alpha < \kappa\}$ is disjoint and $|F_\alpha \setminus V_\alpha| = \kappa$ for each $\alpha < \kappa$. Let $F_\alpha \setminus V_\alpha = \{t_{\alpha\beta} : \beta < \kappa\}$, $T_\beta = \{t_{\alpha\beta} : \alpha < \kappa\}$. Then $\mathfrak{T} = \{T_\beta : \beta < \kappa\}$ is the desired family. \square

For a hypergraph (X, \mathfrak{F}) , $x \in X$ and $A \subseteq X$, we put

$$St(x, (F)) = \bigcup \{F \in \mathfrak{F} : x \in F\},$$

$$St(A, \mathfrak{F}) = \bigcup \{St(a, F) : a \in A\}.$$

Proposition 1.10. *A hypergraph (X, \mathfrak{F}) is kaleidoscopic provided that, for some infinite cardinal κ , the following two conditions are satisfied:*

- (1) $\mathfrak{F} \leq \kappa$ and $|F| = \kappa$ for each $F \in \mathfrak{F}$;
- (2) for any subfamily $\mathfrak{A} \subset \mathfrak{F}$ of cardinality $|\mathfrak{A}| < \kappa$ and any subset $B \subset X \setminus (\bigcup \mathfrak{A})$ of cardinality $|B| < \kappa$ the intersection $St(B, \mathfrak{F}) \cap (\bigcup \mathfrak{A})$ has cardinality less than κ .

Proof. Let $\lambda = |\mathfrak{F}|$ and $\mathfrak{F} = \{F_\alpha : \alpha < \lambda\}$ be an injective enumeration of \mathfrak{F} . By induction we shall construct a transfinite sequence $(\chi_\alpha : F_\alpha \rightarrow \kappa)_{\alpha < \lambda}$ of bijective colorings such that for any ordinals $\alpha < \beta < \lambda$

- (1 $_{\alpha\beta}$) the colorings χ_α and χ_β coincide on $F_\alpha \cap F_\beta$;
- (2 $_{\alpha\beta}$) no distinct points $a \in F_\alpha$ and $b \in F_\beta$ with $\chi_\alpha(a) = \chi_\beta(b)$ lie in some hyperedge $F \in \mathfrak{F}$.

Assume that for some ordinal $\gamma < \lambda$ we have constructed a sequence of colorings $(\chi_\alpha)_{\alpha < \gamma}$ satisfying the conditions (1 $_{\alpha\beta}$) and (2 $_{\alpha\beta}$) for all $\alpha < \beta < \gamma$.

Let us define a bijective coloring $\chi_\gamma : F_\gamma \rightarrow \kappa$. First we show that the union

$$F'_\gamma = \bigcup_{\alpha < \gamma} F_\gamma \cap F_\alpha$$

has cardinality $|F'_\gamma| < \kappa$. Observe that for each $\alpha < \gamma$ we get $F_\alpha \not\subset F_\gamma$. Assuming conversely that $F_\alpha \subsetneq F_\gamma$ and taking any point $v \in F_\gamma \setminus F_\alpha$ we conclude that the intersection $F_\alpha \cap St(v, \mathfrak{F}) \supset F_\alpha \cap F_\gamma = F_\alpha$ has cardinality $\geq \kappa$, which contradicts the condition (2) of the theorem.

Therefore, for each $\alpha < \gamma$ we can choose a point $v_\alpha \in F_\alpha \setminus F_\gamma$. Then for the set $B = \{v_\alpha : \alpha < \gamma\}$ the set $F'_\gamma \subset F_\gamma \cap St(B, \mathfrak{F})$ has cardinality $|F'_\gamma| \leq |F_\gamma \cap St(A, \mathfrak{F})| < \kappa$ according to (2).

For every point $x \in F_\gamma \setminus F'_\gamma$ and every ordinal $\alpha < \gamma$ consider the sets $St(x, \mathfrak{F}) \cap F_\alpha$ and $C_\alpha(x) = \chi_\alpha(St(x, \mathfrak{F}) \cap F_\alpha) \subset \kappa$. The condition (2) implies that the set $C(x) = \bigcup_{\alpha < \gamma} C_\alpha(x)$ has cardinality $|C(x)| < \kappa$.

Let \prec be any well-order on the set F_γ such that F'_γ coincides the initial segment $\{x \in F_\gamma : x < y\}$ for some point $y \in F_\gamma$. Consider the coloring $\chi_\gamma : F_\gamma \rightarrow \kappa$ defined by $\chi_\gamma(x) = \chi_\alpha(x)$ if $x \in F_\gamma \cap F_\alpha$ for some $\alpha < \gamma$ and

$$\chi_\gamma(x) = \min \kappa \setminus (C(x) \cup \{\chi(y) : y \prec x\})$$

if $x \in F_\gamma \setminus F'_\gamma$.

Let us show that the coloring $\chi_\gamma : F_\gamma \rightarrow \kappa$ is bijective. The injectivity of χ_γ follows from the definition of χ_γ and the conditions (2 $_{\alpha\beta}$), $\alpha < \beta < \gamma$.

The surjectivity of χ_γ will follow as soon as we check that for each color $c \in \kappa \setminus \chi_\gamma(F'_\gamma)$ the set $F_\gamma(c) = \{x \in F_\gamma \setminus F'_\gamma : c \in C(x)\}$ has cardinality $< \kappa$. Observe that $c \in C(x)$ if and only if there is $\alpha < \gamma$ and a point $a \in F_\alpha \setminus F_\gamma$ such that $\chi_\alpha(a) = c$ and $x \in St(a, \mathfrak{F})$. The set $A_c = \bigcup_{\alpha < \gamma} \chi_\alpha^{-1}(c) \setminus F_\gamma$ has size $|A_c| \leq \gamma < \kappa$ and by the condition (2), the set $F_\gamma(c) \subset F_\gamma \cap St(A_c, \mathfrak{F})$ has cardinality $< \kappa$. This completes the proof of the bijectivity of the coloring χ_γ .

The conditions $(1_{\alpha\gamma})$ and $(2_{\alpha,\gamma})$ for all $\alpha < \gamma$ follow from the definition of the coloring χ_γ . This completes the inductive step of the construction of the sequence $(\chi_\alpha)_{\alpha < \lambda}$.

After completing the inductive construction, let $\chi : V \rightarrow \kappa$ be any coloring such that $\chi|F_\alpha = \chi_\alpha$ for all $\alpha < \lambda$. The conditions $(1_{\alpha\beta})$ guarantee that the coloring χ is well-defined. The bijectivity of the colorings χ_α , $\alpha < \lambda$, ensures the kaleidoscopicity of the coloring χ . \square

We conclude this section with short discussion of possibilities of transferring above notions and results of quasigroups.

We recall that a *quasigroup* is a set X endowed with a binary operation $*$: $X \times X \rightarrow X$ such that, for every $a, b \in X$, the system of equations $a * x = b$, $y * a = b$ has a unique solution $x = a \backslash b$, $y = b / a$ in X .

In an obvious way the notion of a kaleidoscopical configuration generalizes to quasigroup.

A subset A of a quasigroup X is called

- *kaleidoscopical* if there is a coloring $\chi : X \rightarrow C$ such that $\chi|_{x*A} : x*A \rightarrow C$ is bijective for all $x \in X$;
- *complemented* if there is a subset $B \subset X$ such that the right division $\delta : B \times A \rightarrow X$, $\delta(b, a) = b/a$ is bijective;
- *doubly complemented* if there exists a complemented subset $B \subset X$ such that the multiplication $\mu : A \times B \rightarrow X$, $\mu(a, b) = a * b$, is bijective;
- *self-complemented* if the maps $\mu : A \times A \rightarrow X$, $\mu(x, y) = x * y$, and $\delta : A \times A \rightarrow X$, $\delta(x, y) = x/y$, are bijective.

It follows from the proof of proposition 1.2 that each kaleidoscopical subset in a semigroup is complemented. In contrast, Proposition 1.4 does not generalize to quasigroup.

Example 1.11. *There exists a quasigroup X of order $|X| = 9$ that contains a self-complemented subset $A \subset X$, which is not kaleidoscopical.*

Proof. It is well-known that finite quasigroups can be identified with Latin squares, i.e., $n \times n$ matrices whose rows and columns are permutations of the set $\{1, \dots, n\}$. For $r, s \leq n$ an $(r \times s)$ -matrix (x_{ij}) is called a *partial Latin $(r \times s)$ -rectangle* if $x_{ij} \in \{1, 2, \dots, n\}$ and $x_{lj} \neq x_{ij} \neq x_{ik}$ for any $1 \leq i \neq l \leq r$ and $1 \leq j \neq k \leq s$. By a result of Ryser [7] (see also Lemma 1 in [1, p.214]) each partial latin $(r \times s)$ -rectangle can be completed to a Latin $(n \times n)$ -square if and only if each number $i \in \{1, \dots, n\}$ appears in the rectangle not less than $r + s - n$ times. This extension result allows us to find a quasigroups operation on $X = \{1, \dots, 9\}$ whose multiplication table has the following first three columns:

*	1	2	3
1	1	4	5
2	6	2	7
3	8	9	3
4	4	1	6
5	5	6	1
6	2	7	8
7	7	8	2
8	3	5	9
9	9	3	4

Looking at this table we can see that the set $A = \{1, 2, 3\}$ is self-complemented as $A * A = X = A/A$. Assuming that A is kaleidoscopic, find a coloring $\chi : X \rightarrow A$ such that $\chi|_{x*A}$ is bijective for each $x \in X$. Since $1 * A = \{1, 4, 5\}$ and $4 * A = \{4, 1, 6\}$, the elements 5 and 6 have the same color, which is not possible as $5 * A = \{5, 6, 1\}$ and $\chi|_{5*A}$ is bijective. \square

Corollary 1.8 implies that the size $|K|$ of any kaleidoscopic subset K in a finite group G divides the cardinality $|G|$ of G . The same is true for any finite transitive G -space X .

2. SPLITTING

In this section we present a simple construction of kaleidoscopic configurations in arbitrary G -space, called the splitting construction. Kaleidoscopic subsets constructed in this way will be called splittable.

First we recall some definitions. A map $\varphi : X \rightarrow Y$ between G -spaces is called *equivariant* if $\varphi(gx) = g\varphi(x)$ for all $g \in G$ and $x \in X$. It is easy to see that each equivariant map between transitive G -spaces is surjective and homogeneous.

A function $\varphi : X \rightarrow Y$ is defined to be *homogeneous* if it is κ -to-1 for some non-zero cardinal κ . The latter means that $|\varphi^{-1}(y)| = \kappa$ for all $y \in Y$.

Proposition 2.1. *Let κ be a non-zero cardinal, $\pi : X \rightarrow Y$ be an κ -to-1 equivariant map between two G -spaces and $s : Y \rightarrow X$ be a section of φ . Let $K \subset Y$ be a kaleidoscopic subset and $\chi : Y \rightarrow C$ be an K -kaleidoscopic coloring. Then:*

- (1) *the preimage $\bar{K} = \pi^{-1}(K)$ is a kaleidoscopic configuration in X with respect to any coloring $\bar{\chi} : X \rightarrow C \times \kappa$ such that for each $y \in Y$ the restriction $\bar{\chi}|_{\pi^{-1}(y)} : \pi^{-1}(y) \rightarrow \{\chi(y)\} \times \kappa$ is bijective;*
- (2) *the image $\tilde{K} = s(K)$ is a kaleidoscopic configuration in X with respect to the \tilde{K} -kaleidoscopic coloring $\tilde{\chi} = \chi \circ \pi : X \rightarrow C$.*

Proof. 1. Given any element $g \in G$, we need to check that the restriction $\bar{\chi}|_{g\bar{K}} : g\bar{K} \rightarrow C \times \kappa$ is bijective. To see that it is surjective, take any color $(c, \alpha) \in C \times \kappa$ and using the surjectivity of $\chi|_{gK} : gK \rightarrow C$, find a point $y \in gK$ with $\chi(y) = c$. Since the restriction $\bar{\chi}|_{\pi^{-1}(y)} : \pi^{-1}(y) \rightarrow \{c\} \times \kappa$ is bijective, there is a point $x \in \pi^{-1}(y) \subset \pi^{-1}(gK) = g\bar{K}$ with $\bar{\chi}(x) = (c, \alpha)$, so $\bar{\chi}|_{g\bar{K}}$ is surjective.

To see that it is injective, take any two distinct points $x, x' \in g\bar{K}$. If $\pi(x) = \pi(x')$, then for the point $y = \pi(x) = \pi(x') \in g\pi(K) = \pi(gK)$ the injectivity of the restriction $\bar{\chi}|_{\pi^{-1}(y)}$ implies that $\bar{\chi}(x) \neq \bar{\chi}(x')$. If $\pi(x) \neq \pi(x')$, then the injectivity of $\chi|_{gK}$ guarantees that $\chi(\pi(x)) \neq \chi(\pi(x'))$ and then $\bar{\chi}(x) \neq \bar{\chi}(x')$ as $\bar{\chi}(x) \in \{\chi(\pi(x))\} \times \kappa$ and $\bar{\chi}(x') \in \{\chi(\pi(x'))\} \times \kappa$.

2. Given any element $g \in G$, we need to check that the restriction $\tilde{\chi}|_{g\tilde{K}} : g\tilde{K} \rightarrow C$ is bijective. To see that $\tilde{\chi}|_{g\tilde{K}}$ is surjective, observe that

$$\tilde{\chi}(g\tilde{K}) = \chi \circ \pi(g\tilde{K}) = \chi(g\pi(\tilde{K})) = \chi(gK) = C$$

by the surjectivity of $\chi|_{gK} : gK \rightarrow C$.

To see that $\tilde{\chi}|_{g\tilde{K}}$ is injective, take any two distinct points $x, x' \in \tilde{K} = s(K)$ and observe $\pi(x) \neq \pi(x')$. Since π is equivariant, $\pi(gx) = g\pi(x) \neq g\pi(x') = \pi(gx')$. Since $\pi(gx), \pi(gx') \in gK$ and $\chi|_{gK}$ is injective, $\tilde{\chi}(x) = \chi(\pi(gx)) \neq \chi(\pi(gx')) = \tilde{\chi}(x')$ are we are done. \square

Iterating the constructions from Proposition 2.1, we get the so-called *splitting construction* of kaleidoscopic configurations.

Proposition 2.2. *Let $X_0 \rightarrow X_1 \rightarrow \dots \rightarrow X_m$ be a sequence of G -spaces linked by homogeneous G -equivariant maps $\pi_i : X_i \rightarrow X_{i+1}$, $i < m$. Let $K_i \subset X_i$, $i \leq m$, be subsets such that for every $i < m$ either the restriction $\pi_i|_{K_i} : K_i \rightarrow K_{i+1}$ is bijective or else $K_i = \pi_i^{-1}(K_{i+1})$. If the set K_m is kaleidoscopic in the G -space X_m , then for every $i \leq m$ the set K_i is kaleidoscopic in the G -space X_i .*

Proof. This proposition can be derived from Proposition 2.1 by the reverse induction on $i \in \{m, m-1, \dots, 0\}$. \square

Proposition 2.2 can be alternatively written in terms of invariant equivalence relations.

Given an equivalence relation $E \subset X \times X$ on a set X let $X/E = \{[x]_E : x \in X\}$ be the quotient space consisting of the equivalence classes $[x]_E = \{y \in X : (x, y) \in E\}$, $x \in X$. Denote by $q_E : X \rightarrow X/E$, $q_E : x \mapsto [x]_E$, the quotient map. For a subset $K \subset X$ let $K/E = \{[x]_E : x \in K\} \subset X/E$ and $[K]_E = \bigcup_{x \in K} [x]_E \subset X$.

Let E be an equivalence relation on a set X . A subset $K \subset X$ is defined to be

- *E -parallel* if $K \cap [x]_E = [x]_E$ for all $x \in K$;
- *E -orthogonal* if $K \cap [x]_E = \{x\}$ for all $x \in K$.

Given two equivalence relations $E \subset F$ on X we can generalize these two notions defining $K \subset X$ to be

- *F/E -parallel* if $[K]_E \cap [x]_F = [x]_F$ for all $x \in K$;
- *F/E -orthogonal* if $[K]_E \cap [x]_F = [x]_E$ for all $x \in K$.

Observe that a set $K \subset X$ is E -parallel (E -orthogonal) if and only if it is E/Δ_X -parallel (E/Δ_X -orthogonal). Here $\Delta_X = \{(x, x) : x \in X\}$ stands for the smallest equivalence relation on X .

An equivalence relation E on a G -space X is called G -invariant if for each $(x, y) \in E$ and any $g \in G$ we get $(gx, gy) \in E$. For a G -invariant equivalence relation E on X the quotient space X/E is a G -space under the induced action

$$G \times X/E \rightarrow X/E, (g, [x]_E) \mapsto [gx]_E$$

of the group G . In this case the quotient projection $q : X \rightarrow X/E$ is equivariant. G -Invariant equivalence relations on G -spaces are also called *imprimitivities*.

Proposition 2.3. *Let $\Delta_X = E_0 \subset E_1 \subset \dots \subset E_m$ be a sequence of G -invariant equivalence relations on a transitive G -space X . A subset $K \subset X$ is kaleidoscopic provided*

- (1) *the projection K/E_m is kaleidoscopic in the G -space X/E_m ;*
- (2) *for every $i < m$ the set K is E_{i+1}/E_i -parallel or E_{i+1}/E_i -orthogonal.*

Proof. For every $i \leq m$ consider the G -space $X_i = X/E_i$ and the subset $K_i = K/E_i$ in X_i . Since $E_0 = \Delta_X$, the space X_0 coincides with X . Next, for every $i < m$, consider the equivariant map $\pi_i : X_i \rightarrow X_{i+1}$, $\pi_i : [x]_{E_i} \mapsto [x]_{E_{i+1}}$. This map is homogeneous because of the transitivity of the G -space X_i .

We claim that the maps π_i satisfy the requirements of Proposition 2.2. Indeed, if K is E_{i+1}/E_i -parallel, then $K_i = \pi_i^{-1}(K_{i+1})$. If K is E_{i+1}/E_i -orthogonal, then the restriction $\pi_i|_{K_i} : K_i \rightarrow K_{i+1}$ is bijective.

Now Proposition 2.2 implies that the set $K = K_0$ is kaleidoscopic in $X = X_0$. \square

Proposition 2.3 suggests the following notion that will be cenral in our subsequent discussion.

Definition 2.4. A (kaleidoscopic) subset K in a G -space X is called *splittable* if there is an increasing sequence of G -invariant equivalence relations

$$\Delta_X = E_0 \subset E_1 \subset \dots \subset E_m = X \times X$$

such that for every $i < m$ the set K is either E_{i+1}/E_i -parallel or E_{i+1}/E_i -orthogonal.

Proposition 2.3 implies that each splittable subset in a transitive G -space is kaleidoscopic. What about the inverse implication?

Problem 2.5. *For which G -spaces X every kaleidoscopic configuration $K \subset X$ is splittable?*

3. KALEIDOSCOPICAL CONFIGURATIONS IN MATRIC SPACES

Here we consider each metric space (X, d) as a G -space endowed with the natural action of its isometry group $G = \text{Iso}(X)$. If this action is transitive, then the metric space X is called *isometrically homogeneous*.

Let us recall that a metric space (X, d) is *ultrametric* if the metric d satisfies the strong triangle inequality

$$d(x, z) \leq \max\{d(x, y), d(y, z)\}$$

for all $x, y, z \in X$. It follows that for every $\varepsilon \geq 0$ the relation

$$E_\varepsilon = \{(x, y) \in X^2 : d(x, y) \leq \varepsilon\} \subset X \times X$$

is an invariant equivalence relation on X .

Theorem 3.1. *Let (X, d) be an isometrically homogeneous ultrametric space with the finite distance scale $d(X \times X) = \{\varepsilon_0, \varepsilon_1, \dots, \varepsilon_n\}$ where $0 = \varepsilon_0 < \varepsilon_1 < \dots < \varepsilon_n$. Then every kaleidoscopical configuration K in X is $(E_{\varepsilon_0}, E_{\varepsilon_1}, \dots, E_{\varepsilon_n})$ -splittable.*

Proof. Assume conversely that K is not $(E_{\varepsilon_0}, E_{\varepsilon_1}, \dots, E_{\varepsilon_n})$ -splittable. Then for some $k < n$ the set K is neither $E_{\varepsilon_{k+1}}/E_{\varepsilon_k}$ -parallel nor $E_{\varepsilon_{k+1}}/E_{\varepsilon_k}$ -orthogonal. We can assume that k is the smallest number with that property. By $[x]_{\varepsilon_i}$ we shall denote the closed ε_i -ball $[x]_{E_{\varepsilon_i}}$ centered at a point $x \in X$.

Since K is not $E_{\varepsilon_{k+1}}/E_{\varepsilon_k}$ -orthogonal, there are two points $u, v \in K$ such that $\varepsilon_k < d(u, v) = \varepsilon_{k+1}$. Since K is not $E_{\varepsilon_{k+1}}/E_{\varepsilon_k}$ -parallel, there are points $w \in K$ and $z \in X$ such that $\varepsilon_k < \inf_{x \in K} d(z, x) = d(z, w) = \varepsilon_{k+1}$.

Since X is isometrically homogeneous, we can find an isometry $\varphi : X \rightarrow X$ such that $\varphi(w) = z$. Then $\varphi([w]_{\varepsilon_k}) = [z]_{\varepsilon_k}$ and we can define an isometry $\phi : X \rightarrow X$ letting

$$\phi(x) = \begin{cases} \varphi(x) & \text{if } x \in [w]_{\varepsilon_k}, \\ \varphi^{-1}(x) & \text{if } x \in [z]_{\varepsilon_k}, \\ x & \text{otherwise.} \end{cases}$$

The isometry ϕ swaps the balls $[w]_{\varepsilon_k}$ and $[z]_{\varepsilon_k}$ but does not move points outside the union $[w]_{\varepsilon_k} \cup [z]_{\varepsilon_k}$. Since K is χ -kaleidoscopic, the restrictions $\chi|_{\phi(K)}$ and $\chi|_K$ are bijections onto C . Consequently, $\chi(w) = \chi(z')$ for some point $z' \in [z]_{\varepsilon_k}$. Taking into account that $d(w, z') = d(w, z) = \varepsilon_{k+1} = d(u, v)$ and X is an isometrically homogeneous ultrametric space, we can construct an isometry $\psi : X \rightarrow X$ such that $\psi(u) = w$ and $\psi(v) = z'$. For this isometry, $w, z' \in \psi(K)$ and hence $\chi|_{\psi(K)}$ is not injective, contradicting the choice of the coloring χ . \square

Problem 3.2. Let $\{0, 1\}^\omega$ be the Cantor space endowed with the standard ultrametric generating the product topology. Describe all kaleidoscopic configurations in $\{0, 1\}^\omega$.

Remark 3.3. All closed kaleidoscopic configurations in $\{0, 1\}^\omega$ can be characterized with usage of Theorem 3.1. Among them there are plenty of non-splittable configurations.

A G -space X is called *primitive* if each G -invariant equivalence relation on X is equal to Δ_X or to $X \times X$. It follows that each splitting configuration K in a primitive G -space X is trivial, i.e. either $K = X$ or K is singleton. It is natural to ask if every kaleidoscopic configuration in a primitive G -space is trivial.

The answer to this question is affirmative if X is *2-transitive* in the sense that for any pairs $(x, y), (x', y') \in X^2 \setminus \Delta_X$ there is $g \in X$ such that $(x', y') = (gx, gy)$.

An example of a primitive G -space, which is not 2-transitive is the Euclidean space \mathbb{R}^n of dimension $n \geq 2$ endowed with the action of its isometry group $\text{Iso}(\mathbb{R}^n)$. It turns out that \mathbb{R}^n contain 2^c many unsplittable kaleidoscopic configurations of cardinality c .

To construct a kaleidoscopic subset in \mathbb{R}^n use proposition 1.10 and the following auxiliary definition.

Let (X, d) be a metric space. By $S(x, r) = \{y \in X : d(x, y) = r\}$ we shall denote the sphere of radius r centered as a point $x \in X$.

Definition 3.4. A subset K of a metric space (X, d) is called *rigid* if for any pairwise distinct points $x, y, z \in K$ and numbers $r_x, r_y, r_z \in d(K \times K)$ the spheres $S(x, r_x), S(y, r_y), S(z, r_z)$ have no common point in $X \setminus K$.

Theorem 3.5. Let X be metric space and $G \subset \text{Iso}(X)$ be a group of isometries of X . Each infinite rigid subset $K \subset X$ of cardinality $|K| \geq |G|$ is kaleidoscopic.

Proof. The kaleidoscopicity of the set K will follow from proposition 1.10 as soon as we check that the hypergraph $(V, \mathfrak{F}) = (X, \{gK : g \in G\})$ satisfies the conditions (1)–(2) for the cardinal $\kappa = |K|$. Since $|G| \leq \kappa = |K| = |gK|$ for all $g \in G$, the condition (1) is satisfied.

To show that (2) holds, take any subset $A \subset G$ of cardinality $|A| < \kappa$ and any subset $B \in X \setminus AK$ of cardinality $|B| < \kappa$. We need to show that $|St(B, \mathfrak{F}) \cap AK| < \kappa$. This will follow from $\max\{|A|, |B|\} < \kappa$ as soon as we check that $|St(b, \mathfrak{F}) \cap aK| \leq 2$ for every $b \in B$ and $a \in A$. Assuming conversely that $St(b, \mathfrak{F}) \cap aK$ contains three pairwise distinct points x, y, z we shall obtain a contradiction with the metric independence of K as $d(b, x), d(b, y), d(b, z) \in d(K \times K)$ and b is the common point of the spheres $S(x, d(b, x)), S(y, d(b, y)), S(z, d(b, z))$. \square

In light of Theorem 3.5 it is important to construct a rigid subsets in metric spaces.

Lemma 3.6. Any algebraic independent subset L of affine line in the Euclidean space \mathbb{R}^n of dimension $n \geq 1$ is rigid.

Proof. Identify algebraic independent L with a subset of \mathbb{R} and let Y be any subset of \mathbb{L} with cardinality less than c . It's enough to show that there are no $a \neq b \neq c \in Y$, $r_a, r_b, r_c \in d(Y \times Y) \setminus \{0\}$ and $x \in \mathbb{R}^n \setminus (Y \cup \{p\})$ with $d(x, a) = r_a, d(x, b) = r_b, d(x, c) = r_c$. It follows from the theorem of cosines applying to $\cos(\angle abx) = -\cos(\angle cbx)$ and the observation that there are no such values that $((a-b)(b-c)+r_b^2)(a-c)-(a-b)r_c^2-(b-c)r_a^2 = 0$. Now the proof of the last statement. Let $r_a = s_1 - s_2, r_b = z_1 - z_2, r_c = t_1 - t_2$ where $s_1, s_2, t_1, t_2, z_1, z_2 \in A$. It is a polinom with variable a taking r_a, r_b, r_c as linear functions of a if some of the numbers $s_1, s_2, t_1, t_2, z_1, z_2$ are equal to a or constants. If z_1 or z_2 is equal to a then t_1 or t_2 is. Then the coefficient of a^2 in the equation is $b - c - 2z_2 + b + 2t_2$ or $b - c - 2z_2 + b + 2t_2 + b - c$ and in any case is nonzero that is impossible. The same if one of $\{z_1, z_2\}$ is equal to c . If z_1 or z_2 equals to b and none of them equals to a or c then . If $z_1 \neq a, b, c$ and $z_2 \neq a, b, c$ then as a polinom with variables z_1, z_2 the coefficient of $z_1 z_2$ is 0 only if $|z_1 - z_2| = |s_1 - s_2| = |t_1 - t_2|$ but then $(a - b)(b - c)(a - c) = 0$. \square

Now we are able to prove the promised:

Theorem 3.7. *Let L is continual algebraic independent subset of a line in \mathbb{R}^n . Each subset $K \subset L$ of cardinality \mathfrak{c} is kaleidoscopic in \mathbb{R}^n . Consequently, the Euclidean space \mathbb{R}^n contains $2^{\mathfrak{c}}$ many kaleidoscopic subsets.*

Proof. It follows from Theorem 3.5 and Lemma 3.6 □

Problem 3.8. *The Euclidean space \mathbb{R}^n of dimension $n \geq 2$, does it contain a non-trivial finite or countable kaleidoscopic subset $K \subset \mathbb{R}^n$? If such a set K exists, then its cardinality $|K|$ is not less than the chromatic number of \mathbb{R}^n .*

Let us recall that the *chromatic number* $\chi(X)$ of a metric space X is equal to the smallest number κ of colors for which there is a coloring of X without monochrome points on the distance 1. It is known that $4 \leq \chi(\mathbb{R}^2) \leq 7$ but the exact value of $\chi(\mathbb{R}^2)$ is not known. There is a conjecture that $\chi(\mathbb{R}^n) = 2^{n+1} - 1$, see [10, §47].

Problem 3.9. *Is every finite kaleidoscopic configuration in a (finite) primitive G -space trivial?*

Some examples of infinite G -spaces with only trivial finite kaleidoscopic configurations can be found in [4, chapter 8]

A space \mathbb{R}^n can also be considered as a G -space with respect to the group $G = \text{Aff}(\mathbb{R}^n) = \{\lambda x + a : \lambda \in \mathbb{R} \setminus \{0\}, a \in \mathbb{R}^n\}$ of all affine transformations. The only kaleidoscopic configurations K of cardinality $|K| < \mathfrak{c}$ in this space are singletons as any line that contains more than one point of kaleidoscopic configuration has no distinct points of the same color. On the other hand, every affine subspace of \mathbb{R}^n is kaleidoscopic.

Question 3.10. *Is there any non-splitting kaleidoscopic configuration in \mathbb{R}^n with action of $\text{Aff}(\mathbb{R}^n)$*

Restricting ourself with only translations of \mathbb{R}^n , we get a kaleidoscopic configuration of any size κ , $1 \leq \kappa \leq \mathfrak{c}$. It follows from well-known decomposition of \mathbb{R}^n into the direct sum of rationals and the observation that \mathbb{Z} has a kaleidoscopic configuration of any finite size.

4. HAJÓS PROPERTIES IN GROUPS AND G -SPACES

In this section we reveal the relation of splittability of kaleidoscopic configurations in finite Abelian groups to the Hajós property introduced in [2] and studied in [8], [11], [12].

We recall that an Abelian group G has the *Hajós property* if for each factorization $G = AB$ either A or B is periodic. A subset A of a group G is called *periodic* if $A = gA$ for some non-zero element $g \in G$. Finite Abelian groups with Hajós property were classified in [8]:

Theorem 4.1 (Hajós-Sands). *A finite Abelian group G has the Hajós property if and only if G is isomorphic to a subgroup of a group that has one of the following types:*

$$(p^n, q), (p^2, q^2), (p^2, q, r), (p, q, r, s), (p, p), (p, 3, 3), (3^2, 3), \\ (p^3, 2, 2), (p^2, 2, 2, 2), (p, 2^2, 2), (p, 2, 2, 2, 2), (p, q, 2, 2), (2^n, 2), (2^2, 2^2),$$

where $p < q < r < s$ are distinct primes and $n \in \mathbb{N}$.

A group G is of type (n_1, \dots, n_k) if G is isomorphic to the direct sum of cyclic groups $C_{n_1} \oplus \dots \oplus C_{n_k}$.

Now let us define two weakenings of the Hajós property.

Definition 4.2. An Abelian group G is defined to have

- the *semi-Hajós property* if each complemented subset $A \subsetneq G$ either is periodic or has a periodic complement factor in G ;
- the *demi-Hajós property* if for each factorization $G = AB$ one of the factors A, B either is periodic or has a periodic complement factor.

It is clear that for each Abelian group G

$$\text{Hajós} \Rightarrow \text{semi-Hajós} \Rightarrow \text{demi-Hajós}.$$

Problem 4.3. *Is the semi-Hajós property of finite Abelian groups equivalent to the demi-Hajós property?*

The demi-Hajós property was (implicitly) defined in [9] and follows from the quasi-periodicity of any factorization of the group. In contrast to the Hajós property, at the moment we have no classification of finite Abelian groups possessing the demi-Hajós property. It is even not known if each finite cyclic group has the demi-Hajós property, see Problem 5.4 in [12]. The best known positive result on the semi-Hajós property is the following version of Theorem 5.13 [12]:

Theorem 4.4 (Bruijn-Szabó-Sands). *Each finite Abelian group G of square-free order $|G|$ has the semi-Hajós property.*

We say that a number n is *square-free* if n is not divisible by the square p^2 of any prime number p .

Surprisingly, the following problem of Fuchs and Sands [3, p.364], [9], [12, p.120] posed in 60-ies still is open:

Problem 4.5. *Has each finite Abelian group the demi-Hajós property?*

The “semi” version of this problem also is open:

Problem 4.6. *Has each finite Abelian group the semi-Hajós property?*

The semi-Hajós property is tightly connected with the splittability of kaleidoscopic configurations. In order to state the precise result, let us generalize the definition of the semi-Hajós property to G -spaces.

Definition 4.7. A G -space X has the *semi-Hajós property* if for each kaleidoscopic subset $K \subsetneq X$ there is a G -invariant equivalence relation $E \neq \Delta_X$ on X such that K is E -parallel or E -orthogonal and the set K/E is kaleidoscopic in the G -space X/E .

For finite Abelian groups this definition of the semi-Hajós property agrees with that given in Definition 4.2.

Proposition 4.8. *A finite Abelian group G has the semi-Hajós property if and only if it has that property as a G -space.*

Proof. Assume that the group G has the semi-Hajós property. To show that the G -space G has the semi-Hajós property, take any kaleidoscopic subset $A \subset G$. By Corollary ??, A is complementable and hence has a complemter factor B . Since G has the semi-Hajós property, either A is periodic or else A has a periodic complemter factor. In the latter case we can assume that the complemter factor B is periodic. Consequently there is a non-trivial cyclic subgroup $H \subset G$ such that either $A + H = A$ or $B + H = B$. Consider the quotient group G/H and the quotient homomorphism $q : G \rightarrow G/H$. By Lemma 2.6 of [12], the images $A/H = q(A)$ and $B/H = q(B)$ form a factorization $G/H = A/H \cdot B/H$ of the quotient group G/H . Consequently, the set A/H is complemented in G/H and by Corollary ??, it is kaleidoscopic in G/H .

The subgroup H induces a G -invariant equivalence relation $E = \{(x, y) \in G : x - y \in H\}$ whose quotient space G/E coincides with the quotient group G/H . We claim that the set A is either E -parallel or E -orthogonal. By the choice of the group H , we get $A = A + H$ or $B = B + H$. In the first case the set A is E -parallel. In the second case A is E -orthogonal as $(A - A) \cap H \subset (A - A) \cap (B - B) = \{0\}$.

Now assuming that the G -space G has the semi-Hajós property, we shall prove that the group G has the semi-Hajós property. Given any complemented subset $A \subset G$ we need to show that either A is periodic or else A has a periodic complemter factor. By Corollary ??, the set A is kaleidoscopic in the G -space G . The semi-Hajós property of the G -space G guarantees the existence of an invariant equivalence relation $E \neq \Delta_G$ on G such that A is E -parallel or E -orthogonal and A/E is kaleidoscopic in G/E . It follows that the equivalence class $H = [0]_E$ of zero is a subgroup of the group G . Taking into account that E is G -invariant, we conclude that $(x, y) \in E$ iff $x - y \in [0]_E$. So, G/E coincides with the quotient group G/H . The set A/H , being kaleidoscopic, is complemented in G/H according to Corollary ?? . Consequently, there is a subset $B_H \subset G/H$ such that $G/H = A/H \cdot B_H$. Let $q : G \rightarrow G/H$ be the quotient map and $s : G/H \rightarrow G$ be any section of q .

Now consider two cases. If A is E -parallel, then $A = A + H$ is periodic and complemented as $B = s(B_H)$ is a complemter factor to A in G . If A is E -orthogonal, then the complete preimage $B = q^{-1}(B_H)$ is a periodic complemter factor to A in G . \square

Now we reveal the relation between the semi-Hajós property and the splittability of kaleidoscopic sets.

Proposition 4.9. *If each kaleidoscopic subset of a transitive G -space X is splittable, then X has the semi-Hajós property.*

Proof. To show that X has the semi-Hajós property, fix any kaleidoscopic subset $K \subset X$. By our assumption, K is (E_0, \dots, E_m) -splittable by some increasing chain of invariant equivalence relations $\Delta_X = E_0 \subset \dots \subset E_m = X \times X$. For every $i \leq m$ consider the quotient G -space $X_i = X/E_i$ and let $q_i : X \rightarrow X_i$ be the quotient projection. Also let $K_i = q_i(K) \subset X_i$. By Proposition 2.2, K_i is kaleidoscopic in the G -space X_i . In particular, K_1 is kaleidoscopic in $X_1 = X/E_1$. By Definition 2.4, $K = K_0$ is either E_1 -parallel or E_1 -orthogonal. This means that X has the semi-Hajós property. \square

Theorems 3.1 and Proposition 4.9 imply

Corollary 4.10. *Each isometrically homogeneous ultrametric space with finite distance scale has the semi-Hajós property.*

A G -space Y is defined to be a *quotient* of a G -space X if Y is the image of X under a G -equivariant map $f : X \rightarrow Y$.

Proposition 4.11. *Each kaleidoscopic subset of a G -space X is splittable provided that:*

- (1) *each quotient G -space of X has the semi-Hajós property and*
- (2) *X admits no strictly increasing infinite sequence $(E_n)_{n \in \omega}$ of G -invariant equivalence relations.*

Proof. Assume that some kaleidoscopic subset $K \subset X$ is not splittable. Let $K_0 = K$, $E_0 = \Delta_X$, and $X_0 = X/E_0 = X$. Since X has the semi-Hajós property, there is a G -invariant equivalence relation $E_1 \neq \Delta_X$ on X_0 such that the set $K_1 = K_0/E_0$ is kaleidoscopic in the G -space $X_1 = X_0/E_1$ and K_0 is either E_1 -parallel or E_1 -orthogonal.

By our assumption, K is not splittable, so X_1 is not a singleton. The G -space $X_1 = X/E_1$, being a quotient of X , has the semi-Hajós property. Consequently, for the kaleidoscopic set $K_1 \subset X_1$ there is a G -invariant equivalence relation $\tilde{E}_2 \neq \Delta_{X_1}$ on X_1 such that the set K_1 is \tilde{E}_2 -parallel or \tilde{E}_2 -orthogonal and the quotient set $K_2 = K_1/\tilde{E}_1$ is kaleidoscopic in the G -space $X_2 = X_1/\tilde{E}_1$. Let $q_2^1 : X_1 \rightarrow X_2$ be the quotient projection. The composition $q_2^1 \circ q_1 : X \rightarrow X_2$ determines the G -invariant equivalence relation $E_2 = \{(x, x') \in X^2 : q_2^1 \circ q_1(x) = q_2^1 \circ q_1(x')\}$ on X such that $X/E_2 = X_2$ and $K_2 = K/E_2$ and K_1 is either E_2/E_1 -parallel or E_2/E_1 -orthogonal.

Continuing by induction, we shall produce an infinite increasing sequence $(E_n)_{n \in \omega}$ of G -invariant equivalence relations on X such that for every $n \in \mathbb{N}$ the set $K_n = K/E_n$ is kaleidoscopic in the G -space X/E_n and K is either E_n/E_{n-1} -parallel or E_n/E_{n-1} -orthogonal. But the existence of an infinite strictly increasing sequence of G -invariant equivalence relations on X contradicts our assumption. \square

Since each quotient group of a finite Abelian group G is isomorphic to a subgroup of G , Proposition 4.11 implies:

Corollary 4.12. *If each subgroup of a finite Abelian group G has the semi-Hajós property, then each kaleidoscopic subset $K \subset G$ is splittable.*

Question 4.13. *Assume that a finite Abelian group G has the semi-Hajós property. Has each subgroup of G that property?*

The classification of finite Abelian groups with Hajós property given in Theorem 4.1 implies that this property is inherited by subgroups. Because of that, Corollary 4.12 implies:

Corollary 4.14. *For a finite Abelian group G with the Hajós property, each kaleidoscopic subset $K \subset G$ is splittable.*

Also Proposition 4.11 and Theorem 4.4 imply:

Corollary 4.15. *For a finite Abelian group G of square-free order $|G|$ each kaleidoscopic subset $K \subset G$ is splittable.*

Remark 4.16. It follows from Proposition 4.9 and Corollary 4.12 that Problems ?? and 4.6 are equivalent (and both are open and apparently difficult).

According to an old result of Hajós [2], if in a factorization $\mathbb{Z} = A + B$ of the infinite cyclic group \mathbb{Z} the factor A is finite, then the factor B is periodic. We do not know if the same is true for the groups \mathbb{Z}^n with $n \geq 2$.

Problem 4.17. Assume that $\mathbb{Z}^n = A + B$ is a factorization with finite factor A . Is the factor B periodic? Has A a periodic complements factor?

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